A static biomechanical load carriage model

R.P. Pelot[1], A. Rigby[2], J.M. Stevenson[2] and J.T. Bryant[2]

[1] Department of Industrial Engineering,
Dalhousie University, P.O. Box 1000,
Halifax, Nova Scotia, CANADA, B3J 2X4

[2] Ergonomics Research Group & Clinical Mechanics Group
Queen's University
Kingston, Ontario, CANADA, K7L 3N6

Summary

A two-dimensional biomechanical model of a backpack has been developed which incorporates the primary forces at the shoulder and waistbelt contact points. The model had been validated using instrumented manikins in laboratory experiments. The computer-based formulation allows the user to specify parameters for certain pack features, such as pack mass and volume, and it predicts the resulting contact forces on the bearer. By treating some parameters as decision variables, such as the location of attachment of the shoulder straps to the pack, the model can be used as an optimization tool to achieve a specified objective, such as minimizing the total forces on the bearer. A base case analysis and some variants illustrate this type of analysis. For the example provided, it is not possible to find a feasible solution within the prescribed shoulder-to-waist load ratio. By freeing up other variables, several alternative solutions are presented. This model can be used to easily examine trade-offs in certain pack design decisions.

Introduction

Backpacks are common devices to increase human load carriage capabilities, but when heavily loaded can still place a great burden on the bearer. Many design improvements have been made over the past decades, but more research is still required to fully understand the implications of the associated static and dynamic forces. Parametric analysis of personal load carriage systems allows for increased understanding of relationships between system design characteristics and the impact of these design features on the bearer. A computer-based static biomechanical model of a backpack has been developed to represent the interaction between the pack and the bearer at the principal contact points.

Optimization of the biomechanical model yields the best location for attaching the suspension system components. Various objectives can be considered, such as achieving the best load balance between the shoulders and waist, or minimizing the transverse shear at the lumbar level, which is often associated with discomfort and pain. In the current formulation, the objective is to minimize the sum of the three primary forces acting on the bearer by the pack: the normal force at the shoulders, the vertical force on the hips and the lateral shear on the back at the wasitbelt. A limited set of runs applied to a Base Case backpack illustrates the trade-offs inherent in design decisions.

Literature Review

The literature on personal load carriage is quite broad, and generally falls into one of three categories: physiological studies, biomechanical studies, and subjective appraisal studies. Most of the biomechanical studies concentrate on gait analysis (e.g. DeVita et al., 1991). As there are several comprehensive survey articles on various aspects of load carriage (e.g. Rorke, 1990; Haisman, 1988; Pelot et al., 1995), the following review focuses on some articles directly relevant to the model described in this paper.

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Almost all studies consider the effects of load carriage on the subject through experimentation, and the backpack is part of the pack/person system. Articles examining the isolated pack as a system (static or dynamic) are almost non-existent, however Bobet and Norman (1984) develop a free-body diagram of the trunk/pack system while examining the effects of load placement using EMG. Furthermore, few studies concern themselves with load carriage design details. Exceptions include Bloom and Woodhull-McNeal (1987) who compare internal and external frame packs, and other researchers who consider a double-pack system (e.g. Kinoshita, 1985; Johnson et al., 1995). Certain pack elements are evaluated in isolation, such as the shoulder model presented by Holewijn (1990). Field trials comparing pack features are commonly reported in relevant magazines (e.g. Jenkins, 1992).

In order to establish limitations on contact forces, information is required on the effects of these pressures on the bearer. An article by Sanders et al. (1995) provides an overview of skin response to mechanical stress, while particular injuries arising from load carriage pressures are described in several articles (e.g. Bessen et al., 1987). Studies by Stevenson et al. (1996) have measured strap forces and pressures and correlated them with measures of human discomfort, thereby establishing threshold values on the force levels that may cause discomfort.

The body lean angle under load carriage depends on several factors including pack mass, pack design, level of fatigue, and terrain. Results of such investigations include those by Bloom et al. (1987) and Stevenson et al. (1996). Five to ten degrees is a typical range, but the user may specify this parameter in the model described in this paper.

Since the goal of this biomechanical model is to choose values for certain variables that will optimize an objective, such as minimizing total contact forces, the reader may consult a text such as Winston (1996) to review optimization and formulation in general, linear programming in particular, and non-linear programming, as some optional constraints in the present model introduce non-linear relationships.

Biomechanical Model

A free body diagram of a rigid model of a typical rucksack is shown in Figure 1. The notation is defined at Table 1. The suspension system elements have been numbered from the top down for convenience. Thus the upper shoulder strap's location (d_1), attachment angle (θ_1) and tension (T_1) are consistently subscripted. The subscript '2' refers to the lower shoulder strap portion, and '3' is reserved for certain waistbelt variables. The entire figure and its associated reference coordinates are angled at ß degrees from the vertical to reflect the normal body lean that occurs under heavy loading conditions.

When conducting a parametric analysis, many of the values in the diagram may be treated as variables, to determine the impact of changing them. For the evaluation of a specific pack under given loading conditions, all fixed parameters must be specified and the model is solved for the unknown forces T_1, T_2, F_Z and F_X. To solve for these using the three force balance equations, note that a relationship exists between T_1 and T_2. By modelling the shoulder as a pulley with friction, T_1 and T_2 are related by the friction coefficient and the wrap angle, as shown by equation (1) below (see MacNeil, 1996). The wrap angle α depends on several pack dimensions, notably the attachment points of the upper and lower shoulder straps, shoulder radius, and shoulder-pack distance, as shown in Figure 2 and equations (6) through (10).

Table 1. Notation for Static Biomechanical Model

Suspension System Element	Notation	Definition
Orientation	X	coordinate along pack depth (positive out)
	Z	coordinate along pack height (positive up)
Pack Container	W	the force of the mass of the pack
	v_X, v_Z	position of Centre of Mass
	h_X, h_Z	dimensions of pack container
Bearer	d_4	distance: waistbelt centre to shoulder centre
	d_5	distance: pack back to shoulder centre
	r	radius of shoulder
	r_H	radius of hips
	ß	body lean angle
	γ_1	anatomical lower back angle from vertical
	γ_2	anatomical hip angle from vertical
Waistbelt	T_3	tension in waistbelt
	d_3	distance of waistbelt from bottom of pack
	T_{3C}	compressive force that T_3 applies around the hips
	T_{3C}^N	component of T_{3C} normal to the hips
	T_{3Cf}	force of friction due to T_{3C}
	F^B_Z	lift provided by waistbelt resting on hips
	μ_B	coefficient of friction of waistbelt on hips
	t	thickness of waistbelt
	h_B	height of waistbelt
Shoulder Straps	T_1	tension in upper shoulder straps (LHS and RHS summed)
	T_2	tension in lower shoulder straps (LHS and RHS summed)
	d_1	distance: waistbelt centre to attachment point of upper shoulder strap
	d_2	distance from waistbelt centre to attachment point of lower shoulder strap
	θ_1	upper shoulder strap angle from pack normal
	θ_2	lower shoulder strap angle from pack normal
	α	angle subtended by contact of strap wrapped around shoulder
	μ_S	coefficient of friction of strap on shoulder
	S^N	net force acting normal to the shoulder
Lumbar area	F_X	reaction force of lower back on pack in X-direction
	F_X^N	component of F_X normal to the lower back
	F_{Xf}	force of friction due to F_X
	F^L_Z	lift on the pack from friction and angle at lower back
	μ_L	coefficient of friction of lumbar pad on lower back
	F_Z	total lift force at lumbar contact point of pack

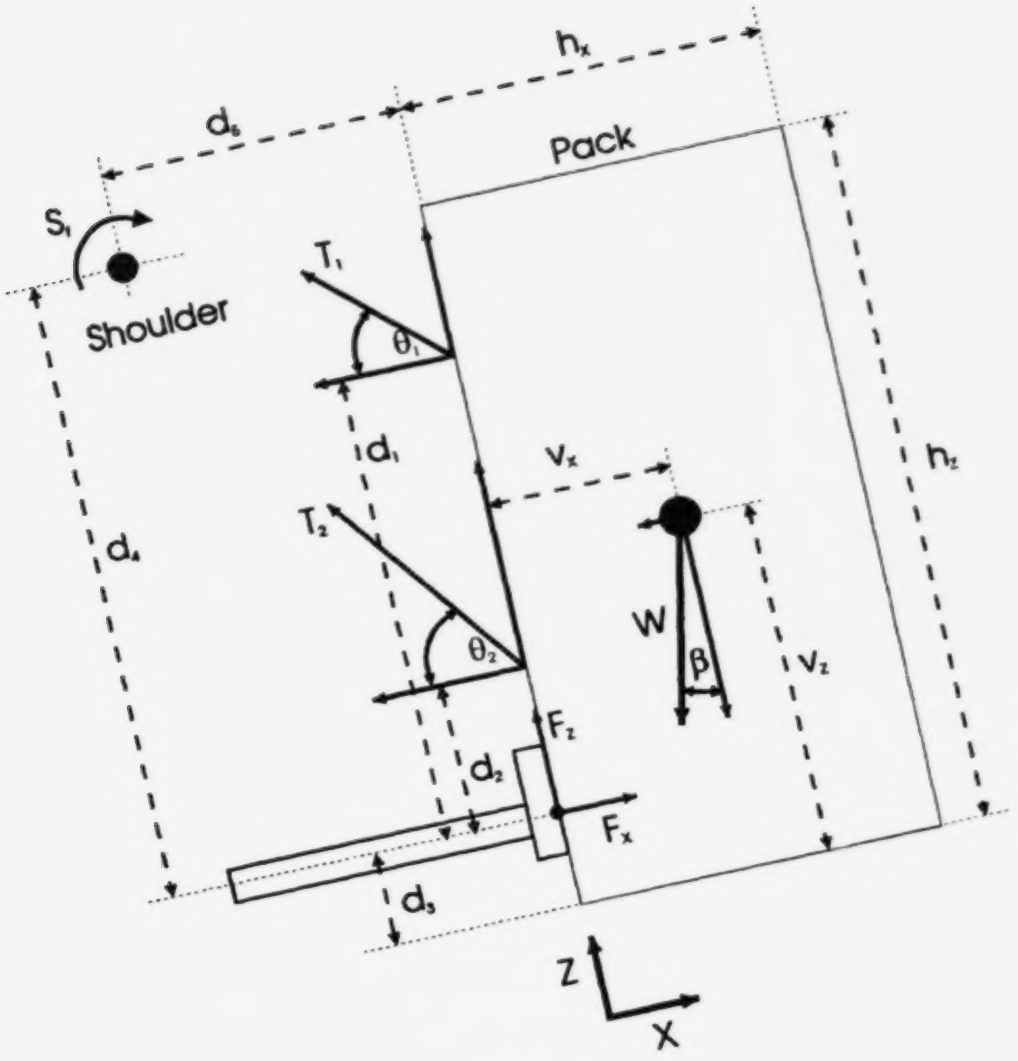

Figure 1. Rucksack free-body diagram with trunk lean

Equilibrium equations:

Pulley equation for shoulder wrap:

$$\frac{T_1}{T_2} = e^{\mu_s \alpha} \qquad (1)$$

Sum of the forces in the X-direction:

$$F_X = W \sin\beta + \left\{ e^{\mu_s \alpha} \cdot \cos\theta_1 + \cos\theta_2 \right\} \cdot T_2 \qquad (2)$$

Sum of the forces in the Z-direction:

$$F_Z = W \cos\beta - \left\{ e^{\mu_s \alpha} \cdot \sin\theta_1 + \sin\theta_2 \right\} \cdot T_2 \qquad (3)$$

Sum of the moments about the center of mass of the pack: **(4)**

$$\left\{ -(v_Z - d_2 - d_3) \cdot \cos\theta_2 - v_X \cdot \sin\theta_2 + e^{\mu_s \alpha} \cdot \left((d_1 + d_3 - v_Z) \cdot \cos\theta_1 - v_X \cdot \sin\theta_1 \right) \right\} \cdot T_2 + (v_Z - d_3) \cdot F_X - v_X \cdot F_Z = 0$$

Isolate T2 by substituting (2) and (3) into (4) and simplifying:

$$T_2 = \frac{W \cdot \left[v_X \cos\beta - (v_Z - d_3) \cdot \sin\beta \right]}{e^{\mu_s \alpha} \cdot d_1 \cdot \cos\theta_1 + d_2 \cdot \cos\theta_2} \qquad (5)$$

Shoulder Wrap angle:

$$\alpha = \pi + \theta_1 - \theta_2 \qquad (6)$$

$$\theta_1 = \tan^{-1}\left(\frac{e_1}{d_5} \right) \qquad (7)$$

$$e_1 = \frac{-2d_5^2(d_4 - d_1) - 2d_5 r\sqrt{d_5^2 + (d_4 - d_1)^2 - r^2}}{2(r^2 - d_5^2)} \qquad (8)$$

$$\theta_2 = \tan^{-1}\left(\frac{e_2}{d_5} \right) \qquad (9)$$

$$e_2 = \frac{-2d_5^2(d_4 - d_2) + 2d_5 r\sqrt{d_5^2 + (d_4 - d_2)^2 - r^2}}{2(r^2 - d_5^2)} \qquad (10)$$

Normal force on shoulders (sum of both sides):

$$S_X^N = T_2 \cdot e^{\mu_s \alpha} \cdot \cos\theta_1 + T_2 \cdot \cos\theta_2 \qquad (11)$$

$$S_Z^N = T_2 \cdot e^{\mu_s \alpha} \cdot \sin\theta_1 + T_2 \cdot \sin\theta_2 \qquad (12)$$

$$S^N = T_2 \sqrt{(\cos\theta_2 + e^{\mu_s \alpha} \cos\theta_1)^2 + (\sin\theta_2 + e^{\mu_s \alpha} \sin\theta_1)^2} \qquad (13)$$

Waist Belt Force:

Tension in belt vs. compressive force on hips, based on hoop stress: $T_3 = T_{3C} / (2\pi)$ **(14)**

Lift due to hip angle (i.e. cone effect) and friction: $F_Z^B = 2\pi T_3 \cdot \cos\gamma_2 \cdot (\sin\gamma_2 + \mu_B \cdot \cos\gamma_2)$ **(15)**

List due to lumbar pad: $F_Z^L = F_X \cdot \cos\gamma_1 \cdot (\sin\gamma_1 + \mu_L \cdot \cos\gamma_1)$ **(16)**

Total lift at waist: $F_Z = F_Z^B + F_Z^L$ **(17)**

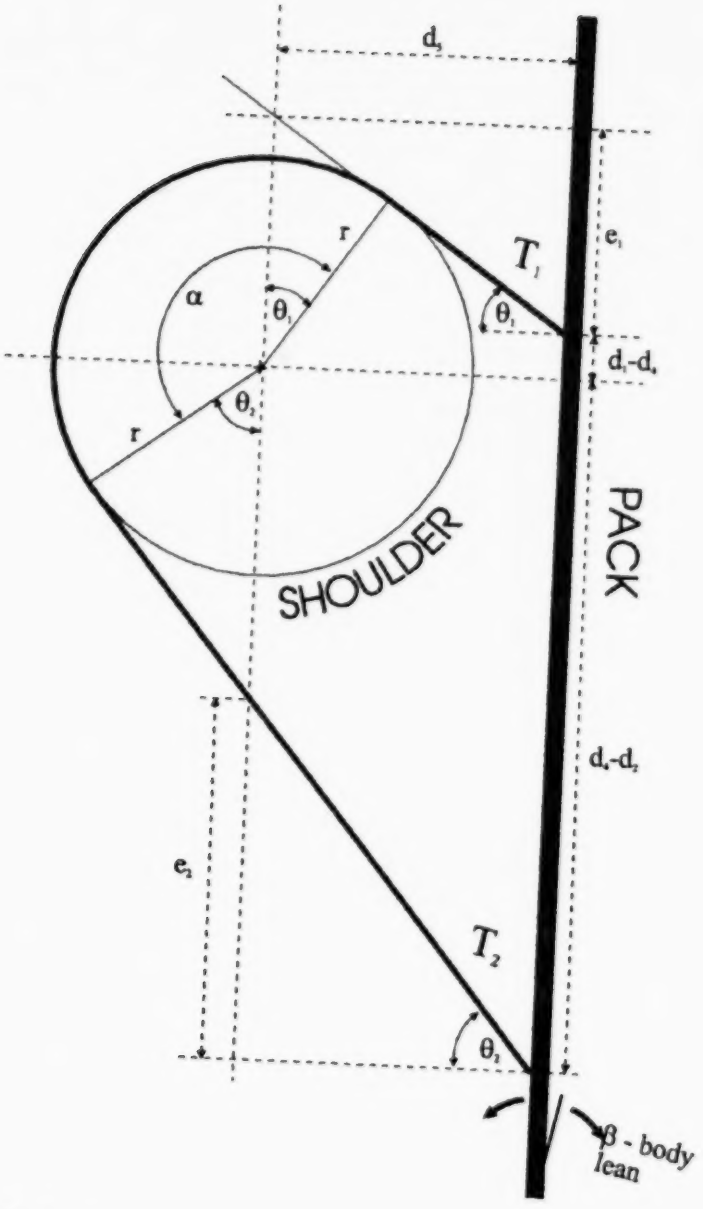

Figure 2. Shoulder wrap angle relations

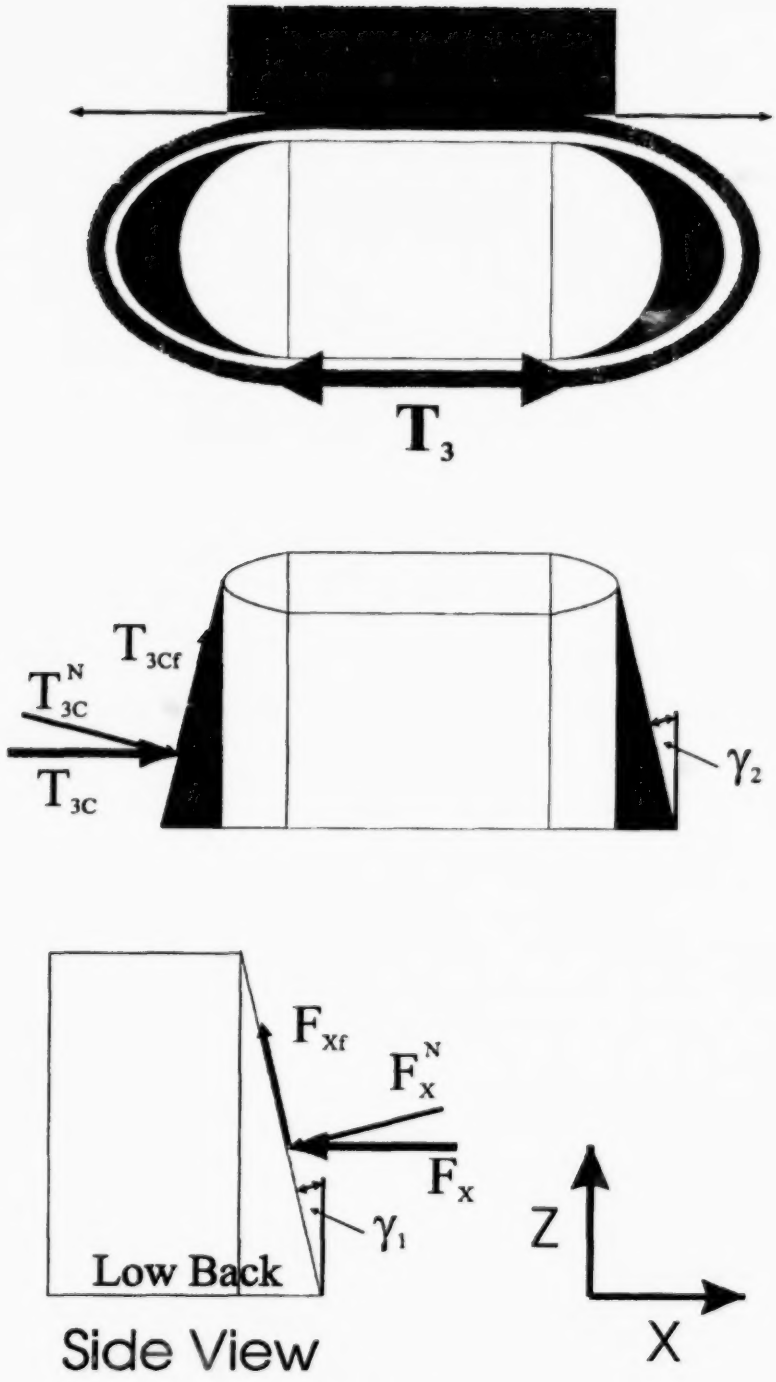

Figure 3. Waistbelt and lumbar pad models

The pack static equilibrium equations for force in the X direction, force in the Z direction, and moments about the centre of gravity can be simplified to the forms given in equations (2) through (5). These expressions can be solved for all of the unknown forces illustrated in Figure 1. However, another quantity of interest is the resultant normal force on each shoulder, S^N (see equations 11 to 13). Finally, the forces at the waist include contributions from the lumbar pad and waistbelt (Rigby, 1997) as shown in Figure 3 and equations 14 to 17. The key assumption is that the lumbar pad provides the maximum possible lift, with the waistbelt contributing the remaining support in the Z direction, if required to maintain static equilibrium of the pack.

The validity of these equations was examined by measuring the forces on several different pack designs mounted on instrumented manikins (Rigby, 1997). Given the respective input parameters for each pack, using the model to predict the unknown forces was quite good in almost all cases, falling within 10% of measured values. The exceptions only occurred in a couple of instances, where the forces were relatively low, and although the absolute error was small, the relative error exceeded this 10% threshold. This relatively simple rigid, two-dimensional model provides valid outputs for the packs and parameters tested.

Optimization of biomechanical model

The first issue is to determine the decision variables, or those variables that may be altered by the designer. To put this in context, there are three categories of values involved in the modelling process:

- *parameters*: externally determined values, which are input to the program, and not changed during the optimization;
- *decision variables*: values which can be changed during the optimization process to best achieve the specified objective;
- *state variables*: values that are calculated explicitly as functions of the parameters, decision variables and/or other state variables.

There is some latitude in selecting decision variables, depending on the purpose of the modelling run. As an initial scenario, assume that only the "heights" of the suspension systems attachment points can be varied (i.e. d_1, d_2, and d_3).

The next step is to formulate the objective function. Various definitions can address the ultimate goal of improving comfort for the bearer. Since there is no unique characterization of the most comfortable load distribution, various alternatives can be considered, with a typical version presented below. Minimizing the normal force on the shoulder, S^N, is used as a surrogate for shoulder comfort. The transverse force on the lower spine has been significantly correlated with pain and discomfort (Stevenson et al., 1996), which can be mitigated by reducing F_X. Finally, excessive vertical forces at the waist should be avoided as a general rule by lowering F_Z. To achieve this, one objective involves minimizing the weighted sum of these three forces, leaving it to the analyst's discretion to set the relative weights. This objective function is presented in the formulation below.

The relationships established by the biomechanical model described in the preceding section act as constraints on the design process. That is, any variable that is altered may affect many other quantities, so that these equations limit the feasible ranges for parameter changes. These relevant constraints are listed in the formulation below.

To complete the model, certain other bounds must be applied to ensure a reasonable result. Note that the biomechanical model formulation incorporates several implicit assumptions, some of which can be relaxed as model analyses progress. First of all, the moment equation was derived on the basis that the upper shoulder strap is attached above the centre of gravity, while the lower shoulder strap and the waistbelt lie below the C of G. Consequently, these dimensions (d_1, d_2 and d_3) are restricted accordingly in the

constraints in the formulation below, although future models can easily circumvent this issue. In any case, the upper shoulder strap must be attached no lower than the lower strap (i.e. $d_1 \geq d_2$). In practice, a finite buffer could be required between them. The lower shoulder strap may be affixed below the centre of the lumbar pad (i.e. effective force application point in Figure 1), but not below the bottom of the rucksack. Similarly, the upper shoulder strap attachment is limited by the height of the pack. Finally, modelling the shoulder as a pulley with friction assumed that the tension is higher in the upper part of the strap (i.e. $T_1 \geq T_2$). There is no explicit control over this in the model, as this assumption guarantees a solution with T_1 larger (if a solution exists). Computer runs may also be conducted where the converse assumption is made, to see if the former case is always valid.

Finally, threshold limits for certain values may be recommended. Previous studies suggest an upper bound of 135 Newtons should be placed on F_X to remain within the comfort zone (Stevenson et al., 1996). Similarly, S^N may be constrained to lie below 280 Newtons. Rules of thumb over many years of experience have also implied that the support for heavy loads be split such that the waist bear about twice the amount of weight than do the shoulders (Pelot, 1995). This guideline does not account for the angle of the resulting normal force on the shoulders, so as a first approximation it is applied simply to the ratio of S^N over F_Z. The degree to which this condition is satisfied can be controlled by requiring the ratio to lie within a prescribed range centered on (2/3) as shown in the constraints below. Continuous improvements in pack suspension system designs may render this prerequisite obsolete.

Optimization formulation

Objective function: minimize $C_1 \cdot S^N + C_2 \cdot F_X + C_3 \cdot F_Z$

where: C_1, C_2, and C_3 are user-specified coefficients

Subject to these constraints:

Equations 1, 2, 3, 5, 6, 7, 8, 9, 10, 15, 16 and 17 (from above)

Additional constraints:

$S^N \leq 280$ $\quad F_X \leq 135$ $\quad d_1 - d_2 \geq 0$ $\quad d_1 + d_3 \leq h_Z$

$d_2 \geq -d_3$ $\quad d_3 \leq V_Z$ $\quad d_1 + d_3 \geq V_Z$ $\quad d_2 + d_3 \leq V_Z$

$$\left| \frac{S_N}{F_Z} - \frac{2}{3} \right| \leq 0.1$$

Base Case analysis

Representative data from a typical commercial pack are presented in Table 2. Aside from pack dimensions, anthropometric data and friction coefficients were established during laboratory experiments (Rigby, 1997). The mass of 30 kg (66 lbs) represents a reasonable load for a typical military mission, although computer runs can be conducted to evaluate the effects of much heavier weights sometimes borne by the soldier. By default, the C of G is assumed to be at the volumetric centre of the pack. Original data is input in specified units, then converted for use in the model. The decision variables are set to the current pack dimensions initially.

Giving equal weight of 1.0 to each force coefficient C_1, C_2 and C_3 when minimizing the objective function yields the results shown in Table 3 for several variations on the Base Case. The optimization procedure does not find a feasible solution for the Base Case itself. In other words, for the given parameters, there is no choice of the three decision variables that satisfy all of the constraints. Further analysis indicates that the restriction being violated is the upper bound on the transverse force at the lumbar level. With the given configuration, it is not possible to keep F_X below 135 Newtons. Removing this constraint, and running the model again results in a feasible solution, listed as Run 2 in Table 3. The minimum F_X attained is 155.3 N.

To achieve this, the shoulder straps are attached to the pack as high as allowed (recall that the lower strap cannot rise above the Centre of Gravity), and the waistbelt as low as possible. Note that $d_3 = 0$ does not mean that the waistbelt is lowered relative to the body, since the waistbelt-to-shoulder distance d_4 is constant, but rather that the bag is raised so that the bottom is flush with the centre of the lumbar pad. The minimum objective value results from the sum of its three force constituents. Thus the model lowers S^N, F_X and F_Z as much as possible. The ratio of shoulder to waistbelt lift is within its prescribed tolerance of (2/3)± 0.1, which means that this constraint is redundant for the conditions of this run. The ratio falls naturally near the desired value. It is clear that the attachment locations of the upper strap and waistbelt in this scenario are too close to the pack edges to be practical, but the purpose of these evaluations is to understand the fundamental design trade-offs. In a more realistic analysis, allowable ranges on the attachment region for each strap can be included in the model.

Table 2. Base Case Data

Biomechanical Load Carriage Model : Base Case			
	ORIGINAL		**CONVERTED**
Description	**Data Units**	**Notation**	**Data Units**
mass of pack + load	30.000 kg	W	294.3 Newtons
depth of pack	34.000 cm	h_X	0.3400 m
height of pack	42.000 cm	h_Z	0.4200 m
CofG from back	17.000 cm	v_X	0.1700 m
CofG from bottom	21.000 cm	v_Z	0.2100 m
shoulder strap top position from WB	43.333 cm	d_1	0.4333 m
shoulder strap bottom position from WB	2.000 cm	d_2	0.0200 m
waistbelt position from pack bottom	6.667 cm	d_3	0.0667 m
waistbelt to shoulder centre	43.000 cm	d_4	0.4300 m
pack back to shoulder centre	14.300 cm	d_5	0.1430 m
shoulder radius	7.000 cm	r	0.0700 m
body lean angle	10.000 deg	ß	0.1745 rads
low back angle	7.000 deg	γ_1	0.1222 rads
hips angle	10.000 deg	γ_2	0.1745 rads
shoulder friction coefficient	0.35 ---	μ_S	0.35 ---
low back friction coefficient	0.35 ---	μ_L	0.35 ---
waistbelt friction coefficient	0.35 ---	μ_B	0.35 ---

Table 3. Optimization results for Base Case (BC) and some variations

Run	**Conditions**	**d_1 (cm)**	**d_2 (cm)**	**d_3 (cm)**	**v_X (cm)**	**v_Z (cm)**	**S^N (N)**	**F_X (N)**	**F_Z (N)**	**Obj (N)**	**S^N/F_Z**
1	Base Case (BC)	infeasible									
2	BC (no limit on F_X)	42.0	21.0	0.0	17	21	127.8	155.3	215.8	498.9	0.592
3	BC with CofG free	32.2	-4.8	4.8	10	37	109.6	103.6	193.5	406.7	0.566
4	BC with CofG free & no limit on S^N/F_Z	38.5	37.0	0.0	10	37	32.7	77.5	270.6	380.8	0.121

It is interesting to examine the impact of allowing the Centre of Gravity to move. Reasonable bounds are imposed by restricting the distance of the C of G from the back to vary between $10 \leq V_X \leq 30$ cm., and the position from the bottom of the bag to lie between $10 \leq V_Z \leq 37$ cm. The output is shown as Run 3 in Table 3. To minimize the forces, the load C of G falls as close to the back and as high as possible. This is consistent with empirical observations in field studies (Hinrichs et al, 1982). The objective value is lower than in the previous run, since allowing the C of G to move corresponds to more degrees of freedom. Notably, each of the three target forces has a reduced magnitude. The lower shoulder strap is attached below the waistbelt, hence the negative distance. The fact that d_2 is equal in value and opposite in sign to d_3 indicates that the shoulder strap is secured right at the bottom of the pack. Both the lumbar transverse force and the shoulder normal force are within the recommended threshold values. The shoulder/waist split constraint is binding at the optimum, which means that the 2:1 ratio is approximately maintained only because of the explicit condition included in the formulation.

Relaxing this last requirement results in the output labeled Run 4 in Table 3. The suspension system attachment points have changed, dramatically in the case of the lower shoulder strap. The effect of raising the shoulder strap attachment points is to remove much of the vertical load from the shoulder, which is then transferred to the hips, resulting in a higher F_Z, and a markedly reduced shoulder-to-waist force split. The transverse lumbar force is significantly reduced and the overall objective function is much lower. Thus artificially promoting a "desirable" shoulder-to-waist load ratio may result in significantly higher forces being exerted on the bearer.

Summary

These optimization results provide an overview of the types of issues that may be explored through this biomechanical model. A particular pack may be represented using the appropriate parameters, and the model can predict the changes associated with specific design changes. Alternatively, monographs may be produced showing the optimal solution for a wide range of combinations of the decision variables. Such a comprehensive set of tests would provide as complete a picture as possible of the interactions inherent in the biomechanical model, which ultimately can enhance the design process. Different objective functions can be introduced, since there is no single answer to the question of what is the "best" combination of forces for the bearer. Finally, the model can be used to perform sensitivity analyses on one or more input parameters.

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PERSONAL AUTHOR: Pelot, R.P.; Rigby, A.; Stevenson, J.M.; Bruant, J.T.

CORPORATE AUTHOR: Defence and Civil Inst of Environmental Medicine, Downsview ONT (CAN)

ABSTRACT: A two-dimensional biomechanical model of a backpack has been developed which incorporates the primary forces at the shoulder and waistbelt contact points. The model has been validated using instrumented manikins in laboratory experiments. The computer-based formulation allows the user to specify parameters for certain pack features, such as pack mass and volume, and it predicts the resulting contact forces on the bearer. By treating some parameters as decision variables, such as the location of attachment of the shoulder straps to the pack, the model can be used as an optimization tool to achieve a specified objective, such as minimizing the total forces on the bearer. A base case analysis and some variants illustrate this type of analysis. For the example provided, it is not possible to find a feasible solution within the prescribed shoulder-to-waist load ratio. By freeing up other variables, several alternative solutions are presented. This model can be used to easily examine trade-offs in certain pack design decisions.

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IDENTIFIERS: Load carriage;Biomechanical models;Load optimization;Ergonomics;Back (anatomy);Lumbar area;Spine (anatomy)

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